Shallow Water Dynamics in the Arabian Gulf and Gulf of Oman

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LONG TERM GOALS

Development of a three-dimensional, high resolution nowcast/forecast system for the Arabian Gulf and Gulf of Oman which encompasses a range of spatial (10 km to 100 m) and temporal scales (hours to months) using the most advanced finite element coastal hydrodynamic models. The modeled dynamics include tidal and wind-driven flow, stratification due to temperature and salinity, river influx, and turbulent mixing processes.

OBJECTIVE

To understand the formation and variability of complex, 3D circulation and mixing patterns in the Arabian Gulf, Strait of Hormuz, and Gulf of Oman at spatial scales of 10 km or less when warranted, over seasonal, tidal, sub-tidal, and storm event time scales. Influences on the thermohaline-driven current structure of the three dominant external forcings in the region, a strong evaporative flux, seasonal wind forcing, and freshwater river discharge, is sought. Another goal is to quantify the seasonal, 3D transport of mass, salt and heat through the Strait of Hormuz and determine its role in the dynamical coupling between the Arabian Gulf and the Gulf of Oman basins. Finally, this study will demonstrate the utility of the finite element approach using state-of- the-art, physically advanced, 3D numerical models. Advantages of the unstructured grid discretization are evident in the placement of open ocean boundaries, localized resolution refinement, and representation of bathymetric and shoreline complexities. A study of this scope, encompassing the Arabian Gulf, Strait of Hormuz, and Gulf of Oman and including resolutions less than 5 km, is unprecedented.

APPROACH

An understanding of coastal circulation and mixing in the study area and development of a nowcast/ forecast system is undertaken through the use of two finite element models. The Dartmouth model, QUODDY, is the pinnacle of long-term development efforts and constitutes the technically and physically most advanced numerical coastal ocean model available. The QUODDY finite element model is 3-D, fully nonlinear, includes tidal, wind-driven, and baroclinic physics, and utilizes advanced turbulence closure (Mellor-Yamada level 2.5 with later enhancements by Galperin, Blumberg, et al.). The second model is ADCIRC-2DDI, which includes nonlinear 2-D, barotropic, physics. The ADCIRC-2DDI finite element model is considerably more computationally efficient and possesses a greater potential for implementation as an operational model. Both models are designed with modular dynamics in which certain mechanisms, such as heat flux, wind forcing, stratification, tides, or river inflow can be independently included or excluded from model equations. This modularity is used to assess the contribution of each of these physical processes in the 3D circulation dynamics.

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The finite element method is unique in that it allows simulation on unstructured grids with enormous gradation in resolution -- thereby supporting very fine local resolution embedded naturally into a regional or shelf-scale model. This approach permits realistic representation of shoreline detail and rapid bathymetric changes which strongly affect the flow field in shallow waters. In addition, boundary forcing may be located in open waters where predictions from global scale models are available and generally, boundaries are far from and have little influence on the region of interest.

An initial diagnostic study of the tidally-induced circulation in the Arabian Gulf is undertaken to establish the barotropic response of the basin prior to the inclusion of more complex baroclinic dynamics within the model. Of particular interest is the tidal residual circulation, that component of the current which remains after removing the oscillatory response at all significant tidal frequencies, and its potential to modify the dominant wind-forced and baroclinic-driven circulation in the Arabian Gulf.

WORK COMPLETED

The domain selected for the model experiments includes the Arabian Gulf, Strait of Hormuz, Gulf of Oman, and extends into deep Indian Ocean waters. The finite element mesh constructed for this domain contains 8550 computational points whose spacing ranges from 0.5-1.0 km near the Shatt al Arab river inflow in the NW Gulf to 46 km in the Indian Ocean. The bathymetry of the Arabian Gulf, taken from the DBDB5 5 minute data base (Naval Oceanographic Office, 1987), is markedly asym metrical about the NW-SE axis of the basin. A deep channel off the Iranian coast contrasts the shal low broad shelf on the Arabian side giving an average basin depth of approximately 50 m. Tidal forcing is applied both at the open boundary and internal to the domain through the tidal potential. Values for tidal constituents prescribed at the open boundary are obtained from results of the Greno ble global tide model (LeProvost et al., 1994). A series of model experiments is run to characterize the barotropic tidal response of the basin and subsequently identify those mechanisms that control the tidal residual circulation and determine the scales at which these residuals are important.

In the progression toward a nowcast/forecast system, an operational run script was designed for the ADCIRC hydrodynamic model off the southern California coast. The automated model set-up includes an interface to the Navy NORAPS Pt. Mugu wind velocity and surface pressure fields, date dependent computations updating tidal factors, the extraction of tidal elevation boundary forcing from a global database, and a restructuring of the ADCIRC model input files for daily execution. Elevation, current magnitude and direction are automatically extracted from the computed model forecast and plotted at pre-specified station locations throughout the model domain. Testing of this real-time forecast capability commenced during support of the Navy JTFEX July 14-25, 1997 at Camp Pendleton, CA. Evaluations of the model performance during this exercise are now underway.

RESULTS

The barotropic tidal response of the Arabian Gulf is established as a mixed semi-diurnal and diurnal tidal environment isolated from the Gulf of Oman co-tidal system by the Strait of Hormuz. With a natural oscillation period of the basin estimated to be approximately 21 hours, the barotropic or external Rossby radius for the basin at a latitude of 27 is just over 330 m, an order of magnitude similar to that of the basin width. As a result, energy enters the Arabian Gulf through the Strait of Hormuz and propagates for each constituent as a Kelvin wave sloping up towards the Iranian coast.

These waves are reflected at the northern head of the Gulf and return along the southern side of the main channel. The broad shelf on the Arabian coast leads to increased frictional damping of the tidal amplitudes and so shifts the tidal amphidromes closer to the Arabian and U.A.E coasts SW of the basin axis. Resonant amplification of the semi-diurnal tides in excess of 1 m is evident in the northern Arabian Gulf and in the Strait of Hormuz. The diurnal response is amplified in the northern Gulf and in the region off the Arabian coast to a lesser degree. Tidally forced elevations computed in the Arabian Gulf compare favorably with published empirical-based co-tidal charts and have been further validated against published tidal station data with agreement in the range of 5-10 cm. Observations of the harmonically analyzed tidal signal indicate that the additional energy generated by the semi-diurnal and diurnal forcing is not all transferred to the mean residual circulation but instead is manifest in both higher and lower frequencies .

As such, tidal residual currents are relatively small, on the order of 2 cm/s, and are found exclusively on broad, very shallow shelf regions in the Arabian Gulf. The most notable areas are off the United Arab Emirate coast, near the cape at Ras-e Jabrin in Iraq, and in the northwest Gulf . Tidally rectified flow is found to be almost entirely generated by advection of the mean flow. The influence of the earthÕs rotation results in slight damping of the residuals and confinement to follow topographic contours. Sensitivity of the tidal residual circulation to the bed stress (figure 1) suggests that these sub-tidal interactions will respond to near-bed turbulence triggered by mixing over the water depth. Thus, increased turbulence in the water column may enhance tidal-induced residual currents and possibly lead to significant interactions with the established thermohaline flow in the basin.

Excessive tidal residual currents in the vicinity of numerous islands dotting the Arabian Gulf and near the ragged shorelines of the Northern Gulf and the Strait of Hormuz highlight the necessity for model resolution finer than 5 km in order to adequately capture the advective processes responsible for generating the tidally rectified flow. No published models to date have utilized resolution to this level.

In working towards a nowcast/forecast system, a real-time run capability has been developed and demonstrated using the finite element hydrodynamic model ADCIRC-2DDI as part of the JTFEX at Camp Pendleton, CA 14-25 July, 1997. This capability provides real-time coastal barotropic currents and sea surface height forced by surface pressure, winds and tides. A series of programs and scripts have been developed to automate the set-up and execution of the ADCIRC-2DDI shallow water finite element model for operational implementation.

IMPACT/APPLICATIONS

Contrary to previous thinking, tidal forcing must be included in any future three-dimensional, baroclinic model of Arabian Gulf circulation. The tidally rectified flow is highly sensitive to bottom drag which can be due either to sea bed frictional forces or turbulent mixing over the water column. In regions of notable mixing and turbulence, enhanced tidal residual currents may have magnitudes which are of the same order as those associated with the baroclinic circulation. So, while the tidal elevations and currents may be small, they can influence the more dominant circulation through nonlinear interactions over the water column in addition to their obvious localized importance. It is also determined that mesh resolution finer than 5 km is necessary to resolve the complex coastal geometry of the Arabian Gulf. Shoreline tortuosity plays a significant role in the generation of tidally rectified flow so its proper representation is required.

The real-time run capability developed and demonstrated using the finite element hydrodynamic model ADCIRC-2DDI will significantly advance the operational capability of the Naval Oceanographic Office (NAVOCEANO) to forecast barotropic currents and sea surface height forced by surface pressure, winds and tides. NAVOCEANO does not currently exercise the ADCIRC-2DDI model in this real-time operational mode but relies on regional tidal data bases generated by a single tidally-forced model forecast.

Detailed knowledge and understanding of the processes governing shallow water dynamics in the Arabian Gulf, Strait of Hormuz, and the Gulf of Oman gained from this modeling effort address Naval needs for anticipating variability in nearshore circulation and water conditions over space and time scales relevant to mine-countermine, amphibious, or special operations in this priority area. High horizontal resolution of tidal elevations and current fields as well as the tidal rectified flow assist in the planning of instrumentation and tactics associated with amphibious operations as well as search and rescue efforts.

TRANSITIONS

The transition of a real-time capability to the NAVOCEANO Warfighting Support Center allows automated, real-time forecasts of tidal and wind-driven circulation using the ADCIRC-2DDI model for the Camp Pendleton area. The general design of the software allows NAVOCEANO personnel to subsequently apply the ADCIRC real-time predictive capability to strategic regions where finite element meshes already exist such as the Yellow Sea, Sea of Japan, Mediterranean Sea, and the east coasts of the U. S.

RELATED PROJECTS

Strong interactions exist with Dan Lynch (Dartmouth College) through the ONR funded "Finite Element Modeling of Coastal Circulation" which is developing a modeling capability in the Yellow Sea quite similar to this projectÕs effort in the Arabian Gulf. Communications are established with ONR sponsored projects by 1) Amy Bower and Jim Price (WHOI) whose work is on the "Pathways of the Arabian Gulf Outflow" and 2) Bill Johns, (U. Miami) who has placed an ADCP mooring in the St. of Hormuz for the period of one year. Funding for the inclusion of baroclinic physics within the ADCIRC finite element model is provided to Rick Luettich (U. North Carolina). The ADCIRC model is deemed as a more appropriate model for transition as part of a nowcast/forecast system than the Dartmouth QUODDY model, which is primarily a research tool.

REFERENCES

Blain, C.A., "Barotropic and Tidal Residual Circulation in the Arabian Gulf", Estuarine and Coastal Modeling, Proceedings of the 5th International Conference, ed. M. Spaulding and A. Blumberg, ASCE, *in review*, 1998.